# Investigation of Correlation Between Yield and Timing Data Obtained from Streak Films


**Brendon Troutman**

**Midshipman, United States Naval Academy**
**Military Academic Research Academy (MARA) Summer Student**
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**Mentors: Dr. Gregory D. Spriggs and MAJ Benjamin Kowash**

**Lawrence Livermore National Laboratory**
**Weapons and Complex Integration**
**AX-Division**


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## Auspices Statement

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## Abstract

When a nuclear detonation occurs, two distinct light pulses are produced. The goal of this project was to analyze archived footage of nuclear explosions conducted by the United States to derive a correlation between the timing characteristic of the light pulses and the yield. Among the archived films are streak films, which record the light pulses with much finer time resolution than most traditional types of high-speed cameras. It was from these streak-camera films that the timing characteristics of the dual light pulses were extracted. The yield of each detonation that was investigated in this report was determined from the high-speed, rotating prism cameras that were used to record radius vs. time data. Due to the limited amount of data analyzed during this internship, accurate timing correlations could not yet be determined. However, it is anticipated that when combined with future analyses accurate timing correlations will eventually be determined.


## 1 Introduction

Nuclear detonations produce dual light pulses with timing parameters $T_{1max}$, $T_{min}$, and $T_{2max}$ (Fig. 1) (Spriggs and Kuran, 2014). Previous research has shown that there is a unique correlation between their values and the yield.

The first pulse is very short-lived and, as such, cannot be captured with the high-speed, rotating-prism cameras used to record fireball growth. Because of the discrete nature of rotating-prism cameras, it is also difficult to extract accurate values for $T_{min}$, and $T_{2max}$ from the second pulse. An alternative type of camera, called a streak camera, uses a continuous film feed and a variety of optical density filters placed over several different apertures to record the light output of an explosion (see Fig. 2). The different filters were meant to increase the chances of obtaining at least one streak on the film that was not under or overexposed and/or to measure spectral effects. The continuous-feed nature of the cameras meant that they were not limited by a frame rate as were the fireball cameras, but rather had an extremely fine time resolution from which $T_{1max}$, $T_{min}$, and $T_{2max}$ could be accurately measured.

In this report, several streak films are analyzed using a Python code developed at the Lawrence Livermore National Laboratory (LLNL) (Yang et al, 2014) to obtain light output vs. time data. The program automatically detects the number of streaks on a film (see Fig. 2), the central pixel location for each streak, the location of the timing marks along the edge of the film, the time of detonation, and the optical density vs. pixel location down the length of any given streak. From these data, $T_{1max}$, $T_{min}$, and $T_{2max}$ were measured. These data were then correlated to the yield.

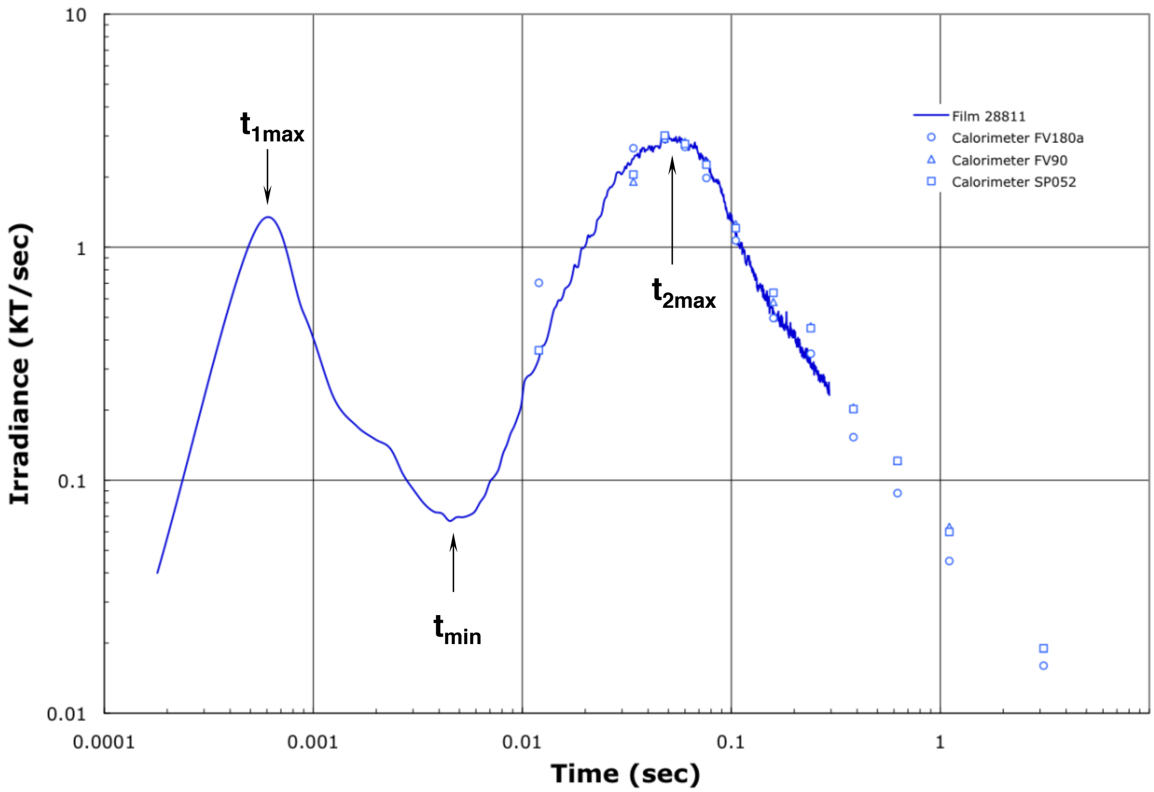



Figure 1. Dual optical pulses of a nuclear explosion (Spriggs and Kuran, 2014)

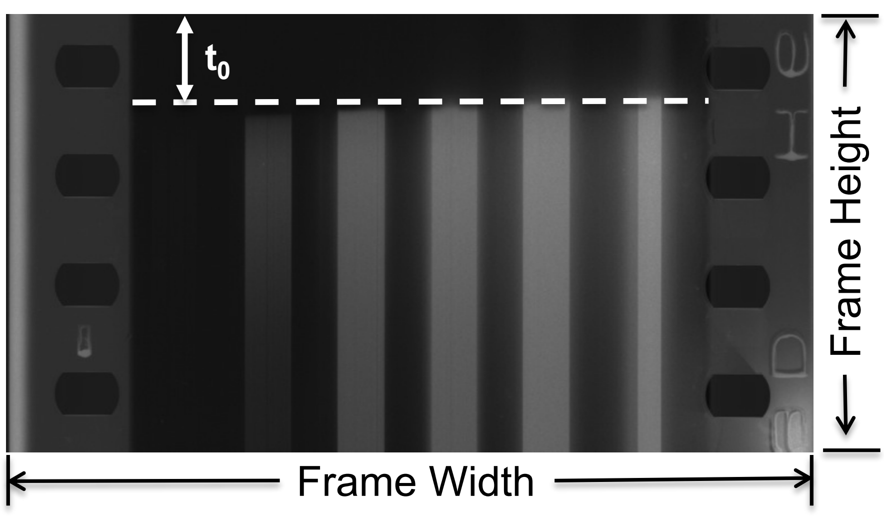



Figure 2. An example of initial detonation on a streak film frame (Yang et al., 2014)

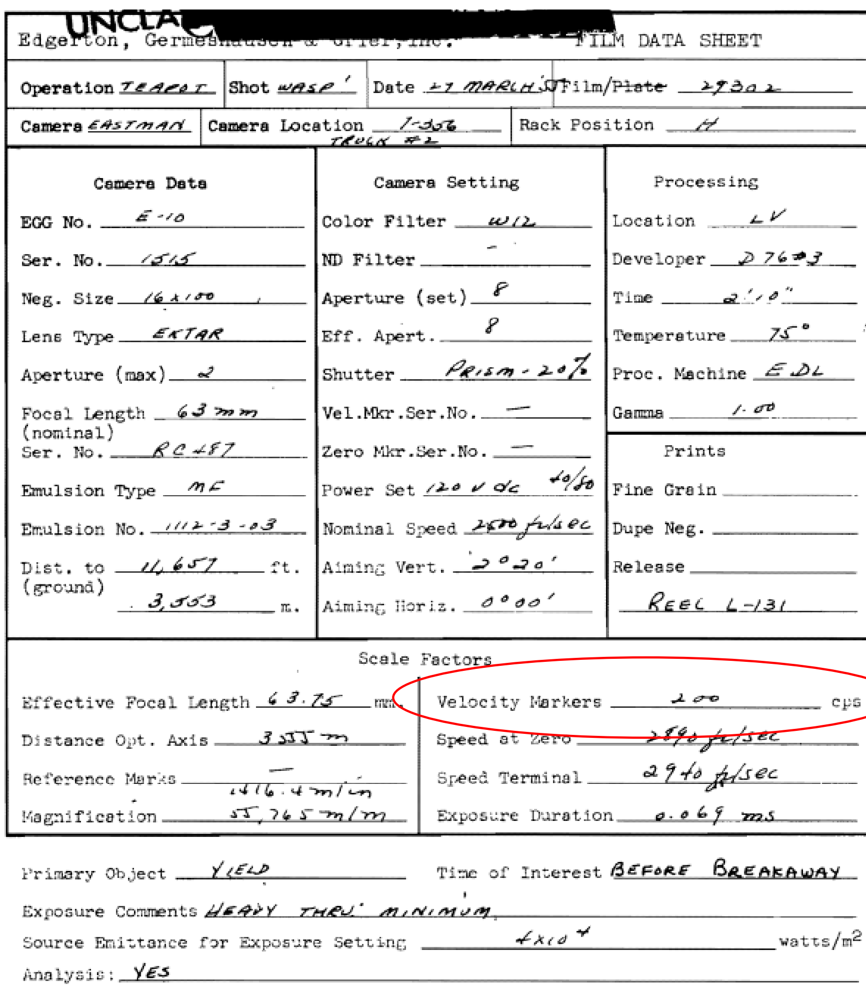
# 2 Methods

## 2.1 Fireball Yield Determination

The yield of each detonation analyzed in this report was determined from fireball radii vs. time data obtained from the rotating-prism cameras. The data were least-squares-fit to Taylor's equation to determine the yield. The methods used to obtain the radii vs. time data are described below.

## 2.2 Data Sheets

Every film has a data sheet that contains information about the film, such as film type, camera location, timing mark information, filters used, developing process, etc. (see Fig. 3). This information is entered into a MATLAB program developed at LLNL (Kowash, 2014) prior to performing some measurement function, such as reading the timing marks.



UNCLA[redacted]

Edgerton, Germe[redacted] FILM DATA SHEET

Operation TEAPOT | Shot WASP' | Date 17 MARCH 55 | Film/~~Plate~~ 29302

Camera EASTMAN | Camera Location 1-356 TRUCK #2 | Rack Position H

| Camera Data | Camera Setting | Processing |
|---|---|---|
| EGG No. E-10 | Color Filter W12 | Location LV |
| Ser. No. 1515 | ND Filter – | Developer D76#3 |
| Neg. Size 16x100 | Aperture (set) 8 | Time 2'10" |
| Lens Type EKTAR | Eff. Apert. 8 | Temperature 75° |
| Aperture (max) 2 | Shutter PRISM - 20% | Proc. Machine EDL |
| Focal Length (nominal) 63 mm | Vel.Mkr.Ser.No. — | Gamma 1.00 |
| Ser. No. RC487 | Zero Mkr.Ser.No. — | Prints |
| Emulsion Type MF | Power Set 120 v dc 40/60 | Fine Grain |
| Emulsion No. 1112-3-03 | Nominal Speed 2600 ft/sec | Dupe Neg. |
| Dist. to (ground) 11,657 ft. | Aiming Vert. 2°20' | Release |
| 3,553 m. | Aiming Horiz. 0°00' | REEL L-131 |

Scale Factors

| | |
|---|---|
| Effective Focal Length 63.75 mm. | Velocity Markers 200 cps |
| Distance Opt. Axis 3555 m | Speed at Zero 2890 ft/sec |
| Reference Marks — 1416.4 m/in | Speed Terminal 2940 ft/sec |
| Magnification 55,765 m/m | Exposure Duration 0.069 ms |

Primary Object YIELD

Time of Interest BEFORE BREAKAWAY

Exposure Comments HEAVY THRU' MINIMUM

Source Emittance for Exposure Setting 4x10^4 watts/m²

Analysis: YES

Figure 3. Data sheet of a film (Spriggs and Kuran, 2014).

## 2.3 Timing Marks

The absolute time relative to the time of detonation corresponding to each frame was determined from an analysis of the timing marks on the film (see Fig. 4). Timing marks were recorded on the films at a specified frequency and, by measuring the distance (i.e., number of frames) between consecutive timing marks, the instantaneous frame rate vs. frame number could be determined.

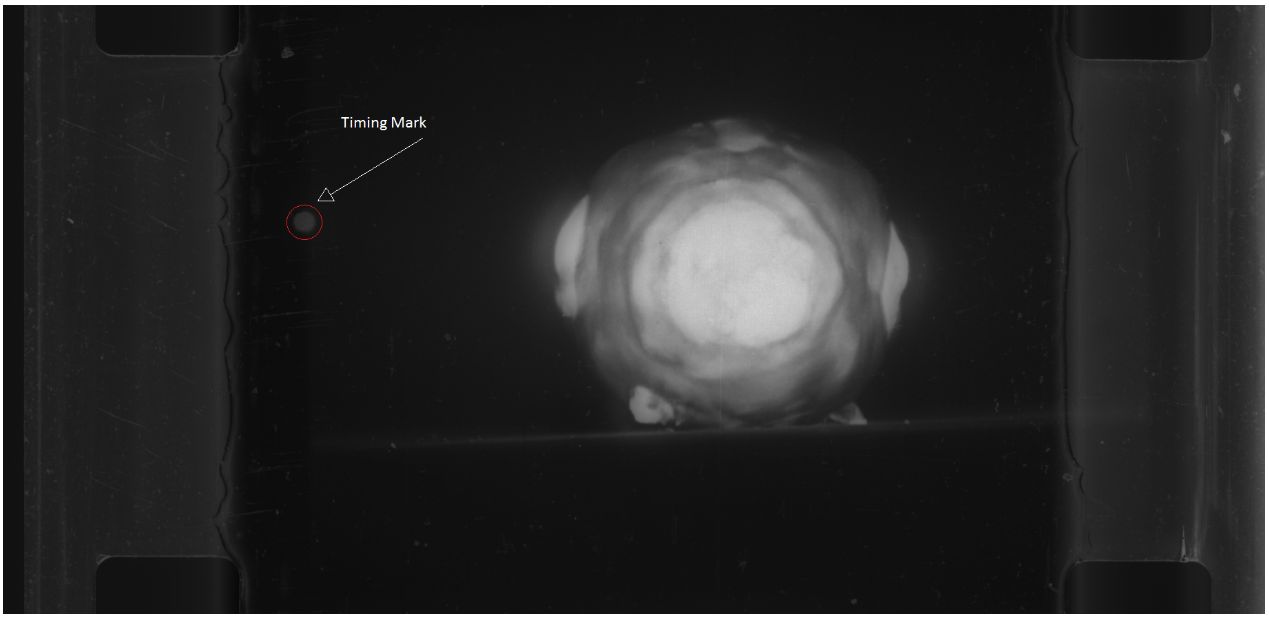



Figure 4. Timing Mark example

## 2.4 Find the Timing Marks.

A MATLAB program developed by LLNL (Kowash, 2014) was used to find the timing marks of the fireball films. This was done by loading a film and its corresponding data sheet into the MATLAB GUI. After selecting the appropriate analysis function and inputting the frame-of-first-light, the user locates a frame with a timing mark and manually selects it. The code then runs automatically using a searching lane of a specified width around the selected timing mark to find the remaining timing marks.

Unfortunately, the version of the MATLAB code that was used during this study had a bug in the SAVE function. As a consequence, it was necessary to copy the timing mark data into an Excel spreadsheet to complete the analysis. The code used to perform this transfer of data is shown below.

```
cps = str2double(FilmData.ScaleFactors{5,1});
```

```
time=MarkNumbers./cps;
timesteps=(time(2:end)-time(1:end-1));
fps=(MarkLocations(2:end)-MarkLocations(1:end-1))./timesteps
```

## 2.5 Instantaneous Frame Rate

The instantaneous frame rate vs. frame number was determined by taking a numerical derivative of the timing mark data. As shown in Fig. 5, these results can be somewhat noisy. Hence, the frame rate data was smoothed by fitting the data to a low-order polynomial. The $\Delta t$ associated with each frame was determined from the inverse of this function evaluated at each individual frame. The absolute time relative to the time of detonation was then determined by summing the individual $\Delta t$'s from all of the previous frames.

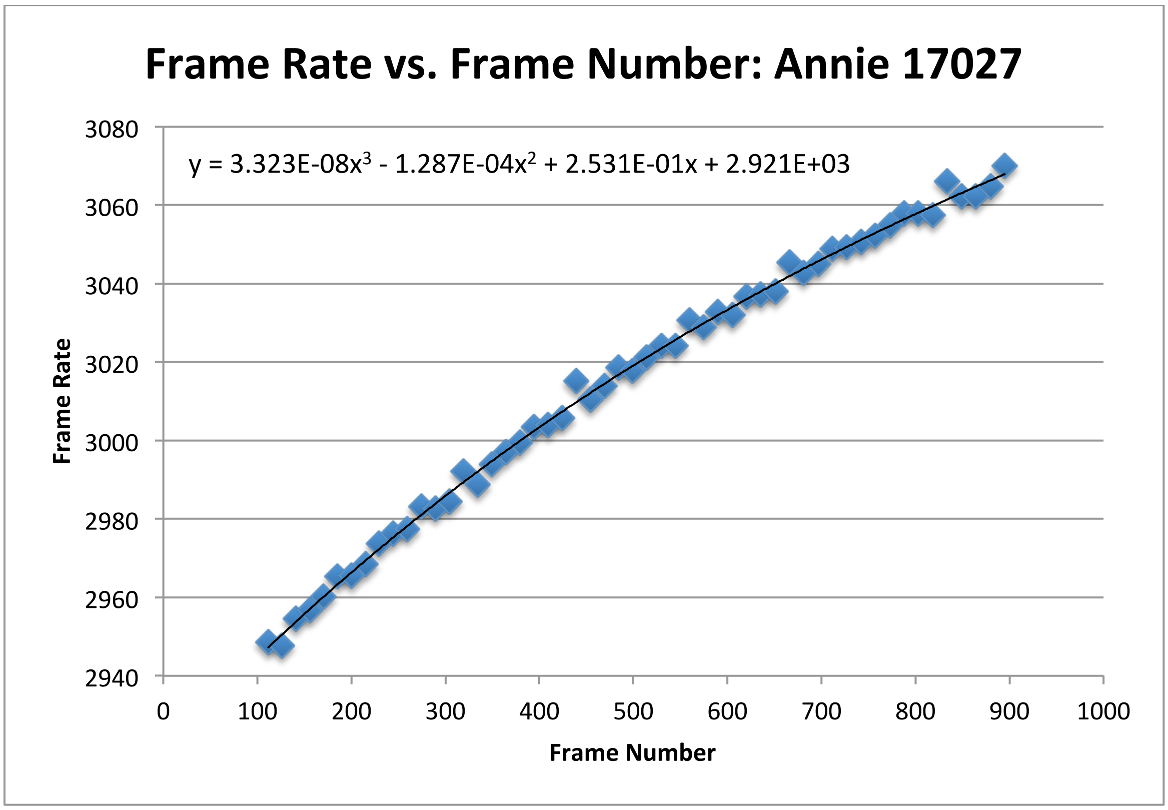



Figure 5. Timing mark data for film Annie 17027

## 2.6 Measurement of fireball radius

A Visual Basic code written at LLNL (Spriggs, 2012) was used to extract fireball radii vs. time data. Fireball films were loaded into this program, along with other parameters that are required to measure the size of the images on the film. Once the film is spatially calibrated, the size of the fireball image on each frame is determined by manually overlaying a circle over the image (see Fig. 6). By knowing the effective focal length of the camera and the distance to ground zero, the actual (real world) size of the fireball can be readily calculated. This process is repeated until the film reaches ~$T_{min}$, at which point in time, the shock wave separates from the fireball and is usually no longer visible on the film (~40 frames on most fireball films).

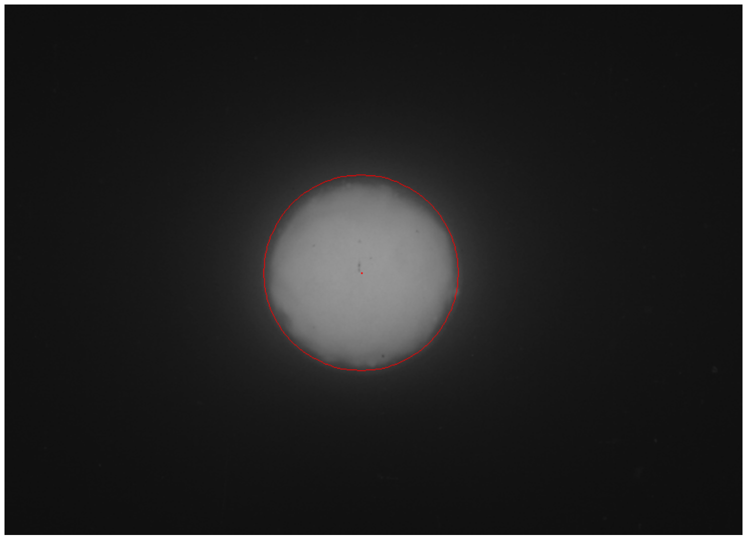


Figure 6. An example of radius measurement

## 2.7 Calculating yield from fireball radius data

The fireball radii vs. time data were entered into an Excel spreadsheet. These data were then least-squares-fit to Taylor's equation using the following LSF equation (Spriggs et al., 2014).

$$R_1 = \frac{\sum R_n t_n^{0.4}}{\sum t_n^{0.8}} \qquad \text{Equation 1}$$

The yield of the detonation was calculated from

$$Y = 32 K \rho R_1^5 \pm \frac{\sigma_Y}{Y} \qquad \text{Equation 2}$$

where $\rho$ is the air density (kg/m3) at the height-of-burst (obtained by Eiler's report), and $K$ is an empirically determined constant ($1.21x10^{-14}$) (Spriggs et al., 2014).

## 2.8 Reading streak films

The Python code (STREAK_ANALYSIS.py) was used to analyze the streak films. This analysis requires writing an .ini file in which the parameters of each film are specified. Among other data, it requires the frame-of-first-light for the film as well as the pixel coordinates in which the streaks and timing marks can be found. The program is then executed in the command prompt, and outputs files that include plots of the light pulses (Fig. 7 and Appendix A) and .txt files that include the data used in the plots.

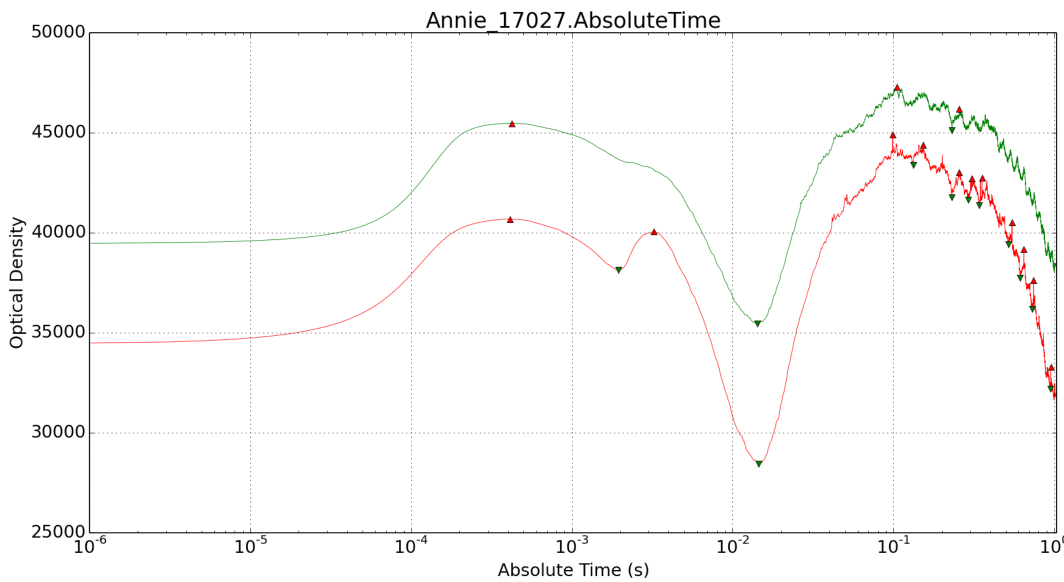



Figure 7. Streak film analysis showing timing pulses $T_{1max}$, $T_{min}$, and $T_{2max}$

## 2.9 Compiling Data

The timing data in the .txt files from the streak analysis was combined with the yield data in a new excel file to compare the results. $T_{min}$ was subtracted from $T_{2max}$ to find $\Delta T$, the time from the point of minimum light output to the second maximum light output. This value was plotted versus yield in order to search for a trend, which would indicate a correlation between the two values.

# 3 Results

## 3.1 Fireball films

Due to several complications with the programs used to analyze the films and a limited time scale for the project, only three tests were analyzed. Five fireball films were analyzed for yield determination. The results of this analysis are presented in Table 1.

Table 1: Fireball films and corresponding yield data

| Film | $R_1$ | Yield (kt) | Average Yield |
|---|---|---|---|
| Annie 17001 | 525.51 | 16.7 | 16.7 |
| Easy 13404 | 505.21 | 13.1 | 12.6 |
| Easy 13406 | 496.41 | 12.0 | |
| How 13801 | 536.11 | 17.3 | 16.8 |
| How 13802 | 528.79 | 16.2 | |

## 3.2 Streak films

Seven streak films were analyzed – three for Easy and How, and one for Annie. The python program used to find the timing data records data for each streak found in a film (ordinarily five). Multiple streaks not only increases the chances of having at least one streak that is properly exposed, but also serves to provide multiple data sets on a single film. Tables 2 through 7 below give the timing data from each streak film. The $\Delta T$ value is calculated using the average of the $T_{min}$ and $T_{2max}$ values from every streak on a given film.

Table 2: Timing data from streak film Annie 17001

| Annie 17027 | $T_{1max}$ (s) | $T_{min}$ (s) | $T_{2max}$ (s) | $\Delta T$ (s) |
|---|---|---|---|---|
| Streak 1 | 4.11E-04 | 1.45E-02 | 9.88E-02 | 8.75E-02 |
| Streak 2 | 4.23E-04 | 1.42E-02 | 1.05E-01 | |
| Average | 4.17E-04 | 1.44E-02 | 1.02E-01 | |

Table 3: Timing data from streak film Easy 13426

| Easy 13426 | $T_{1max}$ (s) | $T_{min}$ (s) | $T_{2max}$ (s) | $\Delta T$ (s) |
|---|---|---|---|---|
| Streak 1 | 2.12E-04 | 1.37E-02 | 1.05E-01 | 9.24E-02 |
| Streak 2 | 2.20E-04 | 1.28E-02 | 1.10E-01 | |
| Streak 3 | 2.14E-04 | 1.29E-02 | 1.10E-01 | |
| Streak 4 | 2.13E-04 | 1.20E-02 | 9.59E-02 | |
| Streak 5 | 2.33E-04 | 1.24E-02 | 1.04E-01 | |
| Average | 2.18E-04 | 1.28E-02 | 1.05E-01 | |

Table 4: Timing data from streak film Easy 13428

| Easy 13428 | $T_{1max}$ (s) | $T_{min}$ (s) | $T_{2max}$ (s) | $\Delta T$ (s) |
|---|---|---|---|---|
| Streak 1 | 1.54E-04 | 4.39E-03 | 1.29E-01 | 1.21E-01 |
| Streak 2 | 1.40E-04 | 2.93E-03 | 1.29E-01 | |
| Streak 3 | 1.68E-04 | 7.15E-03 | 1.25E-01 | |
| Streak 4 | 1.28E-04 | 8.54E-03 | 1.26E-01 | |
| Streak 5 | 1.51E-04 | 1.07E-02 | 1.32E-01 | |
| Average | 1.48E-04 | 6.73E-03 | 1.28E-01 | |

Table 5: Timing data from streak film Easy 13429

| Easy 13429 | $T_{1max}$ (s) | $T_{min}$ (s) | $T_{2max}$ (s) | $\Delta T$ (s) |
|---|---|---|---|---|
| Streak 1 | 2.17E-04 | 1.44E-02 | 1.09E-01 | 9.84E-02 |
| Streak 2 | 2.27E-04 | 1.03E-02 | 1.09E-01 | |
| Streak 3 | 2.01E-04 | 1.02E-02 | 1.13E-01 | |
| Streak 4 | 2.19E-04 | 1.03E-02 | 1.08E-01 | |
| Average | 2.16E-04 | 1.13E-02 | 1.10E-01 | |

Table 6: Timing data from streak film How 13826

| How 13826 | $T_{1max}$ (s) | $T_{min}$ (s) | $T_{2max}$ (s) | $\Delta T$ (s) |
|---|---|---|---|---|
| Streak 1 | 3.28E-04 | 1.14E-02 | 1.28E-01 | 1.16E-01 |
| Streak 2 | 2.93E-04 | 1.06E-02 | 1.25E-01 | |
| Streak 3 | 2.89E-04 | 1.07E-02 | 1.27E-01 | |
| Streak 4 | 2.53E-04 | 1.05E-02 | 1.27E-01 | |
| Streak 5 | 2.97E-04 | 1.16E-02 | 1.28E-01 | |
| Average | 2.92E-04 | 1.10E-02 | 1.27E-01 | |

Table 7: Timing data from streak film How 13827

| How 13827 | $T_{1max}$ (s) | $T_{min}$ (s) | $T_{2max}$ (s) | $\Delta T$ (s) |
|---|---|---|---|---|
| Streak 1 | 3.32E-04 | 9.09E-03 | 1.22E-01 | 1.28E-01 |
| Streak 2 | 2.98E-04 | 9.56E-03 | 1.38E-01 | |
| Streak 3 | 2.80E-04 | 1.05E-02 | 1.38E-01 | |
| Streak 4 | 2.64E-04 | 1.04E-02 | 1.43E-01 | |
| Streak 5 | 2.81E-04 | 1.04E-02 | 1.48E-01 | |
| Average | 2.91E-04 | 1.00E-02 | 1.38E-01 | |

Table 8: Timing data from streak film How 13828

| How 13828 | $T_{1max}$ (s) | $T_{min}$ (s) | $T_{2max}$ (s) | $\Delta T$ (s) |
|---|---|---|---|---|
| Streak 1 | 2.40E-04 | 3.17E-03 | 9.19E-02 | 9.31E-02 |
| Streak 2 | 2.29E-04 | 6.34E-03 | 9.06E-02 | |

| | | | | |
|---|---|---|---|---|
| **Streak 3** | 2.98E-04 | 7.49E-03 | 1.03E-01 | |
| **Streak 4** | 2.26E-04 | 7.94E-03 | 1.02E-01 | |
| **Streak 5** | 3.09E-04 | 8.17E-03 | 1.02E-01 | |
| **Average** | 2.60E-04 | 6.62E-03 | 9.79E-02 | |

## 3.3 Comparison

Figure 9 is a plot of the averages of $\Delta T$ for each shot plotted against the average yields. Obviously, the data is too sparse to discern any type of timing correlation with yield.

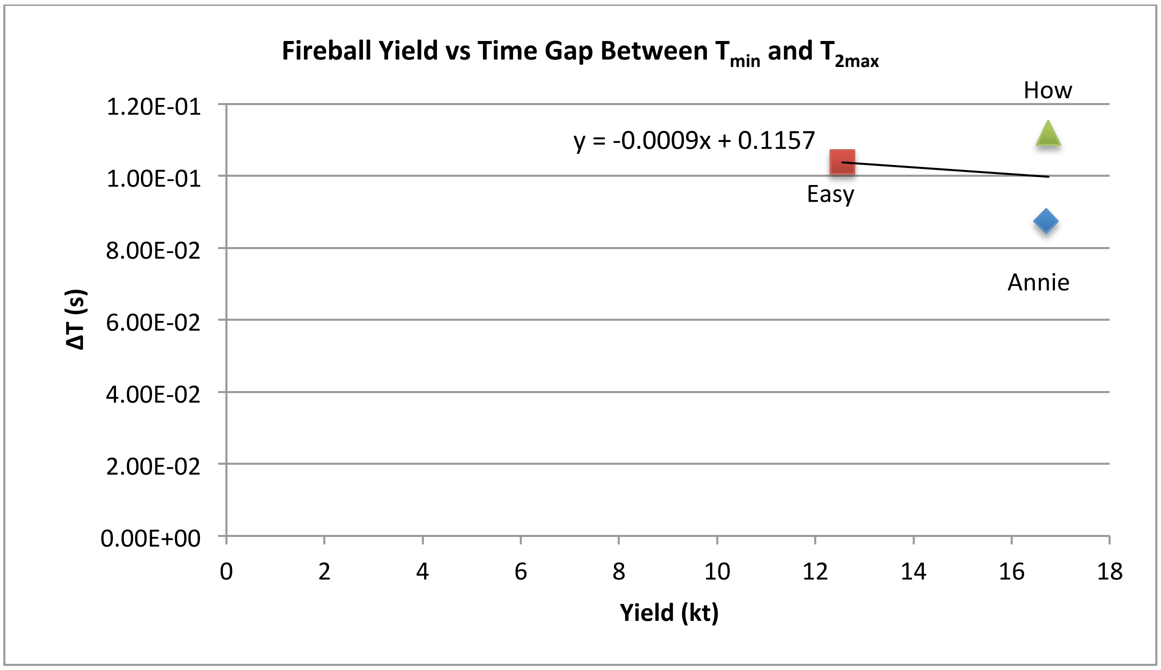



Figure 9. Plot of fireball yield versus $\Delta T$

# 4 Summary

A large part of this project involved gathering data from both fireball and streak films. The tools used to accomplish this were often finicky or under development, making gathering data a time consuming process. Due to the relatively short time scale of the project, a handful of films from only three shots were ultimately analyzed. With only three data points, the results from this project are inconclusive. However, the foundation has been laid for more films to be studied and analyzed using the structure built for this project, making it fairly easy for more data to be collected. With a larger pool of data, a more distinct trend in the correlation between fireball yield and $\Delta T$ may be revealed in the future.

# 5 References

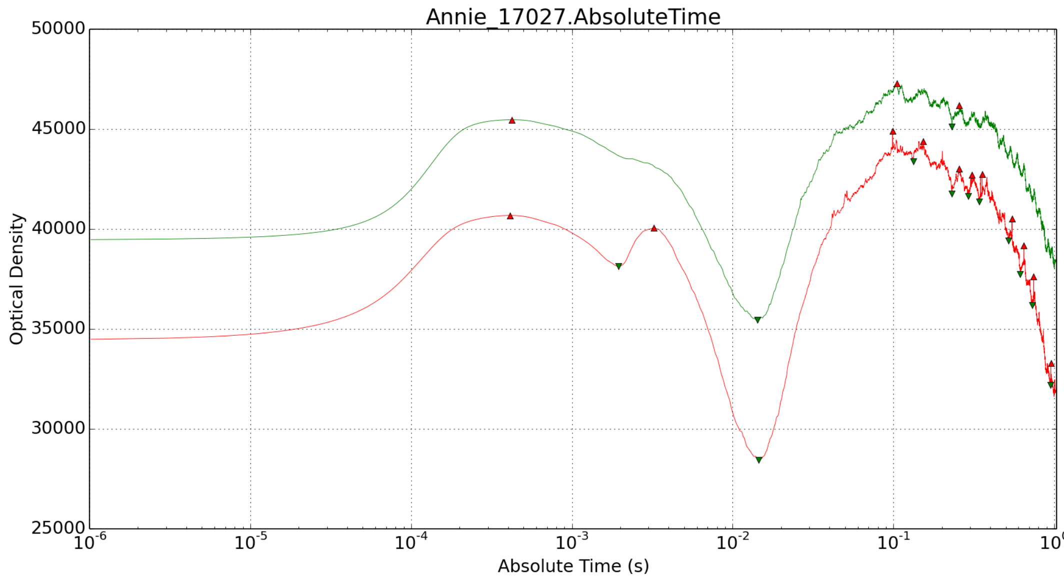

Eilers, D. D., Westervelt, D.R., and Davis, C.G., 1999. Fireball yields, absolute energy scale, United States Atmospheric Nuclear Test Series, LA-CP 00-64 through LA-CP 00-100.

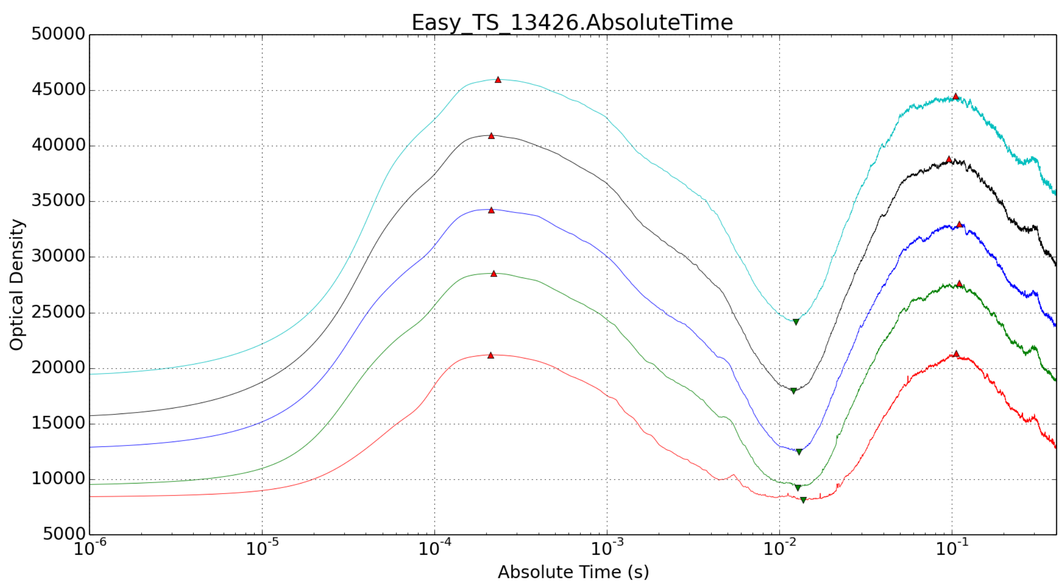
Kowash, Benjamin, MATLAB code (beta version), 2014.

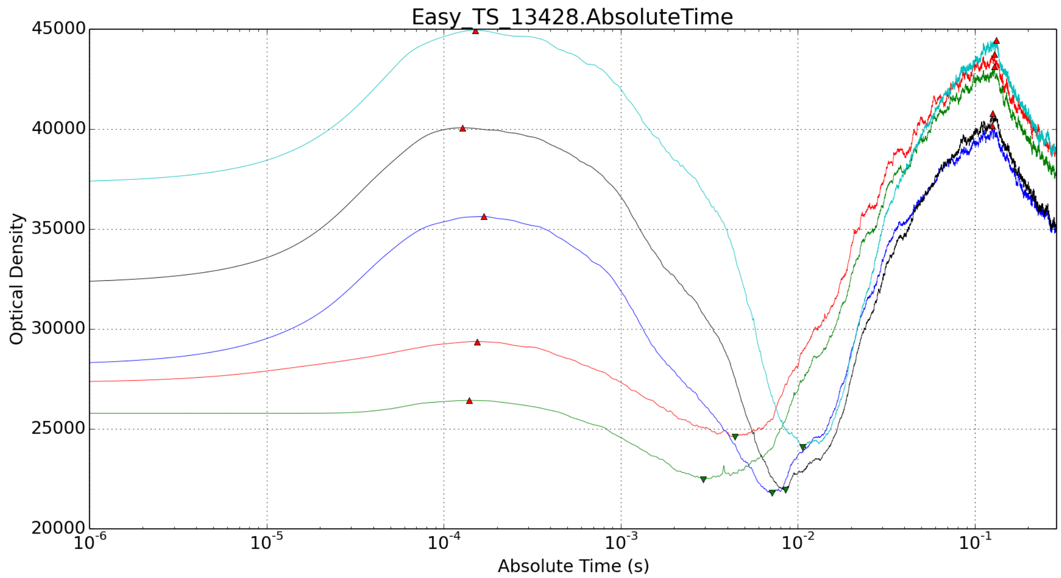
Spriggs, G. D. and Kuran P., 2014. Nuclear Weapon Effects Laboratory Class, LLNL-PRES-642554

Yang, X., Spriggs, G. D., Ramirez, A., and Rodgers, A., 2014. Yield Determination using Optical Data of Nuclear Fireballs on Streak Films (Draft)

# Appendix A – Plots of optical density versus time for streak films




Easy_TS_13428.AbsoluteTime
Optical Density
Absolute Time (s)
45000
40000
35000
30000
25000
20000
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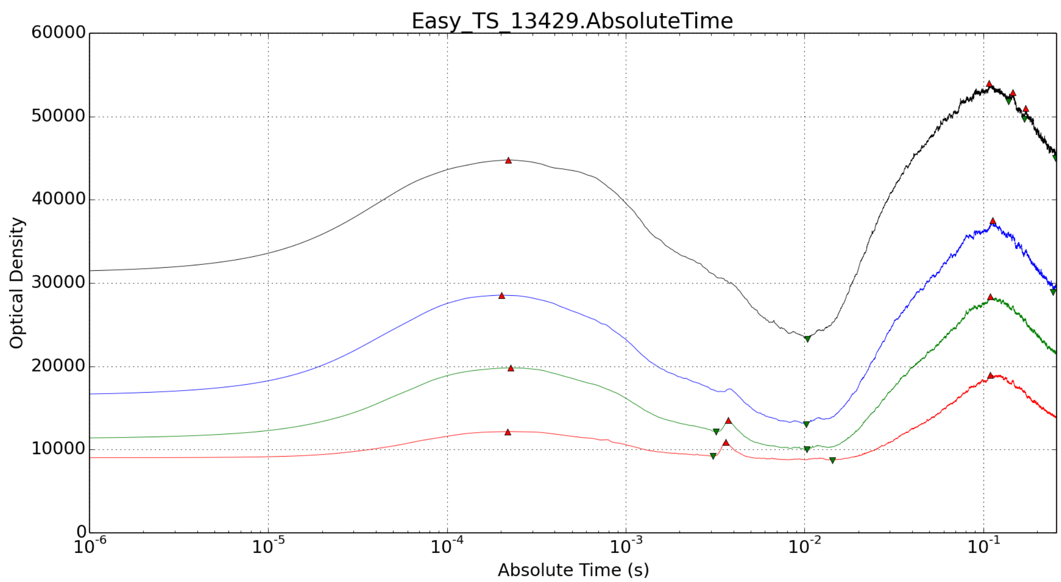
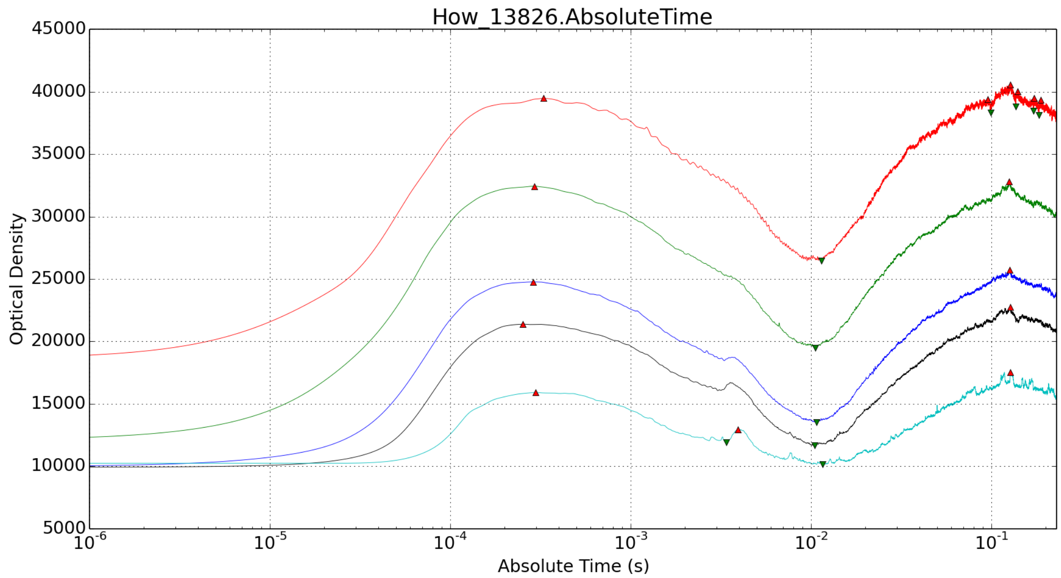
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$


Easy_TS_13429.AbsoluteTime
Optical Density
Absolute Time (s)
60000
50000
40000
30000
20000
10000
0
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$


How_13826.AbsoluteTime
Optical Density
Absolute Time (s)
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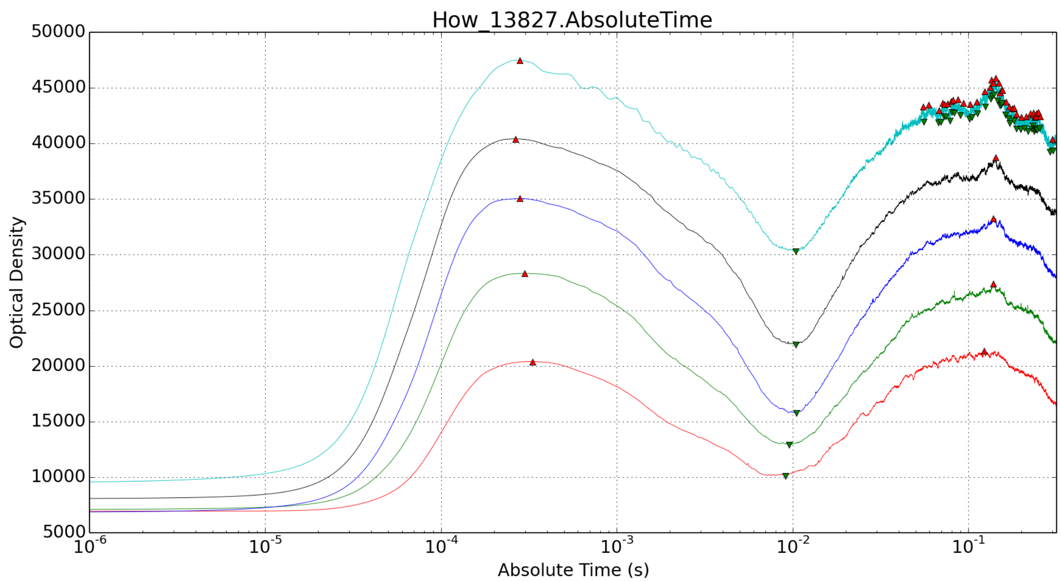
40000
35000
30000
25000
20000
15000
10000
5000
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$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Absolute Time (s)
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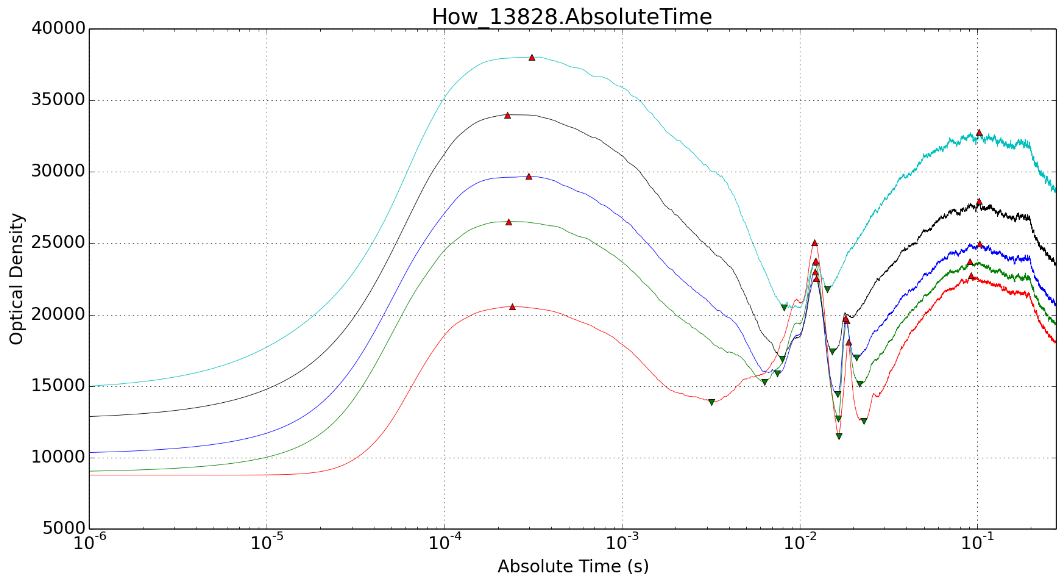
$10^{-1}$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Absolute Time (s)
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$10^{-3}$
$10^{-2}$
$10^{-1}$